

Faint blue objects on the Hubble Deep Field North & South as possible nearby old halo white dwarfs

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ABSTRACT

Using data derived from the deepest and finest angular resolution images of the universe yet acquired by astronomers at optical wavelengths using the Hubble Space Telescope (HST) in two postage-stamp sections of the sky (Williams et al. 1996a,b), plus simple geometrical and scaling arguments, we demonstrate that the faint blue population of point-source objects detected on those two fields (Méndez et al. 1996) could actually be ancient halo white dwarfs at distances closer than about 2 kpc from the Sun. This finding has profound implications, as the mass density of the detected objects would account for about half of the missing dark matter in the Milky-Way (Bahcall and Soneira 1980), thus solving one of the most controversial issues of modern astrophysics (Trimble 1987, Ashman 1992).

The existence of these faint blue objects points to a very large mass locked into ancient halo white dwarfs. Our estimate indicates that they could account for as much as half of the dark matter in our Galaxy, confirming the suggestions of the MACHO microlensing experiment (Alcock et al. 1997). Because of the importance of this discovery, deep follow-up observations with HST within the next two years would be needed to determine more accurately the kinematics (tangential motions) for these faint blue old white dwarfs.

Subject headings: stars: Population II — white dwarfs — stars: evolution — Galaxy: structure — galaxies: halos — galaxies: stellar content

¹Based on observations collected with the Hubble Space Telescope. HST is operated by AURA Inc., under contract with the National Science Foundation.

1. Introduction

The Hubble Deep Field data, in its Northern (HDF-N) and Southern (HDF-S) versions, have been heavily used to study the evolution of very distant galaxies (Livio, Fall and Madau 1998), back to times when the Universe was only a fraction of its present age. Indeed, the main motivation for the acquisition of these very deep images was the study of a small portion of the sky to an unprecedented depth. Yet, these data have also allowed astronomers to study and characterize the faint objects that compose our own Galaxy. In a series of papers (Elson et al. 1996, Flynn et al. 1996, Méndez et al 1996), the stellar sample derived from the HDF-N was used to set constraints on the faint-end of the luminosity function for normal halo field stars, while the shallower, but larger solid-angle data from the HDF-N flanking-fields was used to better refine Galactic structural parameters (Méndez and Guzmán 1998).

In this paper we compare the stellar samples derived from the HDF-N & S pointings. Using a very simple, yet robust, model-independent argument, we demonstrate that the faint blue-objects found on the HDF-N (Elson et al. 1996, Méndez et al. 1996) are indeed Galactic stars, and not distant star-forming regions or compact galaxies as previously suggested (Elson et al. 1996). Our finding is corroborated by independent preliminary tangential motion measurements detected for these faint blue stars (Ibata et al. 1998, Ibata 1998), which also proves that they are not distant Galaxies, but rather nearby stars. Recent evolutionary tracks (Hansen 1998) indicate that, if these faint blue objects are Galactic, then they would be old halo white dwarfs, with ages in the range 10-12 Gyr located at distances of 1 to 2 kpc from the Sun.

2. Point Sources in the Hubble Deep Fields North & South

We have used the source catalogues produced by the Space Telescope Science Institute (STScI) from the combined (deepest), drizzled (spatial resolution enhanced) images from HDF-N and HDF-S available through the WWW. We note that the HDF-N catalogue used here is based on a re-reduction of the HDF-N images, providing some 10% increase in depth or, correspondingly, better signal-to-noise for the brighter sources, than that available from the original images used to detect the faint blue objects. Both, the HDF-N and HDF-S catalogues have been

derived using exactly the same algorithms, procedures, and parameters, and thus, they comprise a very homogeneous and self-consistent dataset.

A critical step is the classification of point-sources *vs.* extended objects. This has been achieved by using a widely tested classifier trained with real images so as to provide the most robust separation of stars *vs.* extended objects by using a neural-network scheme (Bertin, 1995). Figure 1 shows the distribution of CLASS *vs.* magnitude for HDF N & S. CLASS is the probability that SExtractor assigns to an object as being point-like, with CLASS=0 being an extended source and CLASS=1 being a point-like object (CLASS is not a binary classifier but rather a continuous variable that can take any value from zero to one). This figure clearly indicates that there is reliable star-galaxy separation until about $V + I \sim 29$, and that both data sets are quite homogeneous and comparable in depth.

3. The Faint blue Objects as White Dwarfs

Figure 2 shows the frequency of CLASS as a function of this parameter. The large peak at low values of CLASS indicate that the sample is indeed dominated by galaxies, while the smaller, yet conspicuous, peak at larger values of CLASS reveals the truly point-like objects. Visual inspection reveals that all objects with $CLASS < 0.85$ are clearly extended, and thus we have used the very conservative cut at $CLASS > 0.90$ to select our stars. In addition, the original source catalogues provided by STScI had to be trimmed to avoid the many spurious detections near the detector boundaries where the lower signal-to-noise leads to very high source confusion and poor-photometry and shape classification. In the end, our sample consists of 78 point-sources from HDF-N (solid angle of 4.334 arc-min^2) and 98 sources from HDF-S (solid angle of 4.062 arc-min^2). Photometry for these objects was calibrated using the precepts described by Méndez and Guzmán (1998). Worst-case magnitude limits for the shallower HDF-S data (see Figure 1 caption) have been computed from the STScI exposure-time calculator available through their WWW pages. These limits are used here only as a guide, and they do not have a critical impact on the conclusions of this paper. Since the sample analyzed in this paper is several times brighter than the magnitude limit, and the field is not crowded, we do not have to apply any completeness corrections, which should be negligible

above 5σ the sky level, as shown by Paresce et al. (1996) on deep HST images of the globular cluster NGC 6397, acquired with the WFPC2. Actually, our discussion is restricted here to those sources above 15σ the sky level (see Figure 3.)

Figure 3 shows the calibrated color-magnitude diagrams derived from the catalogues. The faint blue stars are clearly seen in both figures, but they appear more numerous on the HDF-S sample. Indeed, this simple fact provides the central argument of this paper. HDF-N is located at Galactic coordinates $(l, b) = (125.89^\circ, +54.83^\circ)$, while HDF-S is located at $(l, b) = (328.25^\circ, -49.21^\circ)$. Therefore, HDF-N is looking towards the outer portion of the Milky-Way, while HDF-S looks inward. It is well known that the stellar density decreases as a function of distance from the Galactic center, either in an exponential fashion for disk-like stars, or as a power of the distance for halo stars (Majewski 1993). Therefore, one would naturally expect to see more stars towards the HDF-S than towards the HDF-N. Is this actually the case? Figure 3 shows the locus for M-dwarfs belonging to the Galactic disk at Heliocentric distances of 1 kpc, and M-subdwarfs belonging to the Galactic halo at distances of 8 kpc, derived from the best available trigonometric parallaxes for these two types of stars (Monet et al. 1992). The characteristic distances adopted for these two types of stars correspond to the typical distances that one expects for them at these magnitudes and Galactic position, as derived from a Galactic model which reproduces the observed HDF-N and Flanking Fields magnitude- and color-counts (Méndez et al. 1996, Méndez and Guzmán 1998).

From Figure 3 (see also Table 1) we see that on HDF-N there are 10 stars within the boundaries allowed by the M-dwarf and subdwarf sequences, while the number of similar objects on HDF-S is 22. Their ratio is roughly a factor of 2. Whether the absolute numbers observed in each field within those boundaries are what one would expect from a standard Galactic model is actually irrelevant to this discussion (however, it has been already shown that the Galactic model predictions and the observed counts do agree on HDF-N and its flanking fields (Méndez et al. 1996, Méndez and Guzmán 1998)). If the faint blue objects are actually extragalactic in nature, as it has been suggested (Elson et al. 1996), then one should not see a variation in their numbers when going from HDF-N to HDF-S, since the Universe is isotropic on large scales (see Table 1). We should remind the reader

that, if these objects are assumed to be extragalactic, they would be located at redshifts of $z \geq 1$ (Elson et al. 1996), and at these scales the angular correlation function (which measures the number of galaxy pairs at a given angular separation, in excess of a random distribution) has been found to be zero to within 5×10^{-4} for angular separations larger than 6° (Maddox et al. 1990, the HDF-N and HDF-S are 165° apart in the sky). However, what we find from Figure 3 is that the number of faint blue objects is 5 on HDF-N and 10 on HDF-S, their ratio being a factor of two, almost exactly as it is for normal stars. This argument suggests that the faint blue objects are not extragalactic and that, furthermore, their space distribution follows that of normal Galactic stars. Assuming a Poisson distribution, the probability of seeing 10 sources on HDF-S when 5 are expected is only 1.3% (account has to be made for the different solid-angles covered by both samples). Therefore, even though the samples are small, the observed difference in the number of expected objects if they had an isotropic N-S distribution is highly significant. Additional indication that the faint blue objects are actually nearby is provided by Ibata and Lewis (1998, and Ibata 1998) who have obtained preliminary tangential motions for the point-sources on HDF-N using a two-year baseline on HST. They find that four of the five faint blue objects do have detectable tangential motions at a 3σ level or more, thus ruling out the hypothesis that they are extragalactic objects (their motions are actually consistent with halo kinematics at 1 to 2 kpc, see below). A more robust proper-motion determination would require additional observations with HST within the next two years to increase the time baseline for the tangential motion measurement.

4. Conclusions and implications for the nature of dark matter in the Galaxy

The MACHO microlensing experiment has found that a significant fraction of the dark matter is baryonic, and made of objects with $0.5 M_\odot$ (Alcock et al. 1997). They have suggested white dwarfs (WDs) as possible candidates because they have the right mass and, though very numerous, old ones would be quite faint to have remained undetected thus far. Figure 3 shows the locus of old WDs as recently computed by Hansen (1998) using the latest atmospheric models and opacity tables, and confirmed observationally on the cool & low-luminosity WD LHS 3250 (Harris et al. 1999). It is clear from this figure that the faint

blue objects do fall in the region predicted by these models, as originally pointed out by Hansen himself for HDF-N. This fact, plus the discussion in the preceding paragraph, indicates that we have detected a population of old faint and blue white dwarfs belonging to the Galactic halo, and located at Heliocentric distances of up to 2 kpc. This finding has profound implications for the nature of dark matter in our own galaxy. If the objects that we have detected are actually old WDs from the halo, then their expected number in the HDF-N *vs.* the HDF-S should follow that of the general halo population. Is this actually case? For a density law similar to that exhibited by halo field tracers (e.g., RR-Lyraes or Blue Horizontal-Branch stars, (Sluis and Arnold 1998)), i.e. $\rho \sim R^{-3}$ with an axial ratio of 0.8, where R is the distance from the Galactic center, we find that the expected number ratio of halo stars between the HDF-N and HDF-S is about 1.71. Therefore, the factor of two increase when going from HDF-N to HDF-S is consistent with their being associated with the halo field (given the uncertainties in the halo density law).

If, as the preceding discussion suggests, we have detected a population of faint blue old halo WDs in the vicinity of the Sun. What is their contribution to the local Galactic mass budget? Their mass contribution ($M_{\text{Halo WD}}$) is given by:

$$M_{\text{Halo WD}} = N_{\text{Halo WD}} \times \mu_{\text{WD}} = 8.46 \times 10^{-8} \Omega \rho_{\odot} R_{\odot}^3 \int_0^{d_{\text{lim}}} \frac{r^2}{R^3} dr \quad (1)$$

where $N_{\text{Halo WD}}$ is the number of halo WDs with typical mass μ_{WD} observed on HDF, Ω is the solid angle (in squared arc-min) subtended by the HDF, ρ_{\odot} is the mass density of this component in the solar neighborhood (in M_{\odot}/pc^3), R_{\odot} is the solar Galactocentric distance (in pc), r is the Heliocentric distance, and d_{lim} is the maximum Heliocentric distance sampled by the HDF data.

Assuming a typical WD mass of $0.6 M_{\odot}$, and a maximum sampling distance of 2 kpc (see Figure 3), we obtain a value of $4.64_{-0.66}^{+0.33} \times 10^{-3} M_{\odot}/pc^3$ for the local ($R_{\odot} = 7.5$ kpc) mass density of halo WD. On the other hand, dynamical studies of the Galaxy indicate a *local* value for the mass density of dark matter of $1.26 \times 10^{-2} M_{\odot}/pc^3$ (this mass density is equivalent to $0.19 M_{\odot}/pc^3$ at the Galactic center on a density law of the type adopted by Bahcall and Soneira 1980). Therefore, our HDF sample accounts for about 1/3 to

1/2 of the dark matter in the Milky Way.

The analysis of gravitational microlensing events of stars in the Large Magellanic Clouds (Alcock et al. 1997) places the mass of the lensing objects in the range $0.5_{-0.2}^{+0.3} M_{\odot}$, suggesting that they might actually be old WDs. Furthermore, the MACHO collaboration finds that about half of the dark matter halo of the Milky Way could be composed of those old WDs. These two suggestions by the MACHO group seem to be in agreement with our analysis of the HDF faint blue data and, basically, resolves about half of the dark matter problem in our Galaxy (the other half still being unaccounted for by ordinary matter).

Our derived mass density assumes that *all* of the faint blue objects on both HDF-N & S are indeed halo white dwarfs. However, it seems that at least one of these objects is quite close to the halo subdwarf sequence on HDF-N (see Fig. (3), upper panel), while some of the fainter stars on HDF-S (see Fig. (3), lower panel) have colors that are not inconsistent with those of M subdwarfs, although being some 2 magnitude fainter in I than normal M subdwarfs. As mentioned earlier, Méndez et al. (1996) have demonstrated that the faint blue population could not be accounted for with current Galactic models, and therefore required something new. Since no similar comparison has been produced yet for HDF-S, we have run some Galactic models to predict the number and distribution of M-dwarfs from the disk and halo from the same model used for the analysis of the HDF-N. In the range $20 \leq V \leq 26$ and $0 \leq B-V \leq 1.9$, mostly encompassing the locus of stars on Fig. 3, the model described by Méndez et al. (1996) (with the changes indicated by Méndez and Guzmán 1998) predicts between 18 and 22 stars, depending on one's choice of scale-height for main-sequence disk stars (still a somewhat uncertain model parameter). This good agreement of the normal M dwarfs with the models (see Table 1) is, of course, no compelling assurance for the "need" of a new population of stars, since the samples are still quite small: A 1σ Poisson fluctuation on the count of 22 model-predicted stars would account for a large fraction (almost 5 out of 10) of the faint blue stars as being part of the stellar content of normal models - which do not include halo WDs.

We should also consider that errors intrinsic to the calculation of WD tracks are actually not large, 0.1 mags or less, and mostly coming from uncertainties in the temperature and pressure behavior in the atmosphere (cool white dwarfs are convective to the photo-

sphere), although the results seem to be fairly insensitive to mixing length prescriptions (Hansen 1999). Another uncertainty is from opacities not as yet included in the models, in particular the higher H_2 level transitions. Even though lower transitions are dominant, these higher transitions might take notches out of the flux between the broad absorption bands, and this would likely make WD appear bluer. Given that the lower bands are the dominant opacity contributor, the general trend should be robust, but the detailed colors could vary somewhat, perhaps as much as 0.5 magnitudes. Finally, a bigger uncertainty, which can reach several tenths of a magnitude, comes from the fact that cool WD atmospheres are distinctly non-blackbody and have many spectral signatures, making them quite susceptible to the adopted band-passes. Calculations for both HST and Johnson & Kron-Cousins colors can differ by up to about 0.5 mags. Hansen has adopted, for the models used here, the synthetic magnitudes described in Section 5.2 of Holtzman et al. (1995). This was done because transformations such as those described in the earlier sections of the Holtzman paper are based on standard stars, and will not hold well for stars whose spectra do not resemble the standard stars. Furthermore, the procedure in section 5.2 also matches well with those used in other WD atmosphere calculations, making comparisons easier. After calculating the WFPC2 magnitudes, magnitudes and colors on the VRI system were computed using the transformations defined on Table 10 of the Holtzman et al. paper, following thus the same procedure employed to convert our observed HST magnitudes to the Johnson-Cousins system. Given all these uncertainties, it is reassuring that the more recent independent model calculations by Saumon and Jacobson (1999), and which overcome some of the simplifying assumptions of the earlier models, do agree with Hansen's original calculations. In particular, Saumon and Jacobson conclude that very cool ($T_{\text{eff}} < 3500$ K) halo ($t_{\text{age}} > 10$ Gyr) WDs would have $V-I < 1.4$.

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TABLE 1
OBSERVED NUMBER OF GALACTIC STARS, FAINT BLUE POINT SOURCES, AND EXTRAGALACTIC OBJECTS IN THE
HDF-S AND HDF-N.

Object	HDF - N	HDF - N (norm) ^a	HDF - S	Normalized ratio HDF-S / HDF-N ^b
Galactic stars	10	9.37	22	2.35 ± 0.90
Faint blue	5	4.69	10	2.13 ± 1.17
Extragalactic ^c	566	530.48	486	0.916 ± 0.057

^aNormalized to same solid angle as HDF-S.

^bPoisson noise from the original, unnormalized, counts.

^cGalaxies selected in same magnitude and color range as the faint blue sources.

Fig. 1.— SExtractor CLASS parameter *vs.* HST V+I (uncalibrated) magnitude from the co-added (and deepest) F606W and F814W drizzled-combined frames produced by STScI for HDF-N (upper panel) and HDF-S (lower panel). The total effective on-target integration times that went into the combined V+I frames are 64.63 and 50.44 hours for the northern and southern deep fields, respectively. It is apparent that we can reliably separate point-sources (CLASS ~ 1) from extended objects (CLASS ~ 0) down to $V + I \sim 29$.

Fig. 2.— Specific frequency of stars as a function of CLASS for HDF-N (blue) and HDF-S (red). We have trimmed our point-like sample in a very conservative way at CLASS ≥ 0.90 . Objects with CLASS < 0.85 are clearly extended in the individual V and I drizzled-combined frames. Objects with $0.85 \leq \text{CLASS} < 0.90$ fall below our magnitude cutoff (see Figure 3), and therefore do not affect the conclusions of this paper (see text).

Fig. 3.— Color-magnitude diagrams in calibrated Johnson-Cousins I *vs.* V-I for point sources from the HDF-N (upper panel) and the HDF-S (lower panel). The red dotted line is the locus for disk M-dwarfs at 1 kpc from the Sun, while the green dotted line is the locus for sub-dwarfs at a Heliocentric distance of 8 kpc. The solid black lines indicate the 15σ magnitude limits imposed by the exposure time in the combined HDF I frame (horizontal line) and the V combined frame (diagonal line). Only objects above the intersection of these two solid lines are firm detections, with good star-galaxy separation. The red stars are bona-fide Galactic stars as predicted, in number and location on the CMD, from standard Galactic models. The faint blue stars are shown by the blue symbol. The true nature of these objects is revealed as old, cold halo WDs (see text). The blue dotted line indicates the theoretical predicted locus for halo WDs of $0.6 M_{\odot}$ at 1 kpc, while the solid line indicates the locus for the same stars at 2 kpc. WDs in the mass range 0.5 to $0.9 M_{\odot}$, encompassing the full range of models computed by Hansen, exhibit a similar color magnitude distribution. The blueness of the WD tracks occurs at an age of about 10 Gyr and $T_{\text{eff}} \sim 3,500$ K. Uncertainties in the physics of the models and the transformation of its predictions to the observational plane can account for up to 0.5 mag in the predicted WD colors (Hansen 1999).





